Comparison of latent heat flux estimates over Australia

Matthew F. McCabe[1], Yi Y. Liu[1], Raghuveer Vinukollu[2], Hongbo Su[3], Jason P. Evans[4] and Eric F. Wood[2].

[1] *School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia*
[2] *Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ USA*
[3] *Center for Research on Environment and Water (CREW), Calverton, Maryland, USA*
[4] *Climate Change Research Centre, University of New South Wales, Sydney, Australia*

Email: mmccabe@unsw.edu.au

Abstract: Documenting the water cycle through modelling and observation is needed for more fundamental understanding of water exchanges in Earth's coupled systems. Spatially and temporally consistent characterization of the hydrological cycle has been a research goal of numerous investigations for many years. Recent applications of sophisticated modelling approaches has seen the development of a number of continental and global scale land surface schemes designed for this purpose, providing insight into the movement of water through the terrestrial system. The Global Land Data Assimilation System (GLDAS) is one such programme that has delivered significant insights into water and energy exchange over the Earth's terrestrial surfaces. While there are a number of numerical modelling based approaches that seek to describe terrestrial water and energy cycles, an operational, observationally based and temporally consistent data set for continental scale evapotranspiration is not currently available. As a result, important insights available from such data do not contribute to model assessment and calibration.

This study compares latent heat fluxes derived from two land surface models, which have been run over Australia for a 2 year period, with satellite observations and in-situ rainfall measurements. The two land surface models, component schemes of the Global Land Data Assimilation System, are evaluated against a newly developed remote sensing based flux dataset, to identify their degree of hydrological coherence. The remote sensing product utilizes multiple satellite sensors onboard NASA's Aqua satellite to estimate instantaneous heat fluxes at the time of satellite overpass, providing an unprecedented spatial coverage of continental scale evaporation over Australia. An assessment of the agreement between these distinct data sets is undertaken, with a focus on the reproduction of spatial and temporal patterns of latent heat flux over portions of the Australian continent.

Keywords: *Land surface models, evapotranspiration, latent heat flux, satellite remote sensing, precipitation.*

1. INTRODUCTION

Accurate estimation of evaporation (E) is of considerable interest to meteorological, climatological and agricultural investigations. Evaporation, or the latent heat flux (λE) (where λ is the latent heat of vaporization), characterizes the physical process that links the land surface with the atmosphere in describing water transport through the hydrological cycle. While it is of critical importance in understanding the partitioning of water distribution across Earth's terrestrial surface, accurately monitoring its spatial variation, particularly at temporal resolutions of most interest (daily), is notoriously difficult. Spatial and temporal scaling issues, errors in forcing variables, heterogeneity in surface characteristics and simplifications in our process understanding, all limit the capacity to accurately monitor flux development and variability.

Two of the most significant advances in progressing the spatial representation of latent heat fluxes in recent years have been the development of large scale numerical models of the land surface and satellite remote sensing approaches to estimate surface fluxes (see Kalma et al., 2008 for a review of such approaches). While these techniques have produced considerable opportunity for large scale water balance investigations, they have generally progressed as parallel efforts, rather than as complementary approaches. Indeed, while remote sensing observations of numerous hydrological variables are available, relatively limited integration of these data has been undertaken in land surface modelling investigations, with a singular focus on data assimilation of the near-surface soil moisture being the predominant approach.

One of the critical limitations in large scale land surface modelling is the provision of adequate (and accurate) data with which to evaluate model output. Calibration and validation of land surface schemes is still primarily undertaken through comparison of streamflow: an inadequate variable for distributed assessment, particularly when one considers that land surface models do not generally account for dams and reservoirs that are ubiquitous features of river networks. There are also major issues in regions of the world that do not have a dense network of gauging stations. A clear opportunity for bridging the observation-model divide is to utilize independently retrieved satellite based estimates as an evaluation data source for land surface models.

In this contribution, we present a preliminary analysis of the continental scale assessment of the latent heat flux as derived from large scale land surface modelling, using a recently developed (and independently derived) remote sensing based product, developed at Princeton University. We assess the capacity of the remote sensing product to reproduce the range and variability of measured flux data through evaluation against an in-situ tower site. Then, the degree of hydrological consistency (McCabe et al., 2008) between model and remotely observed fluxes is assessed through comparison with Bureau of Meteorology (BoM) precipitation fields to assist in evaluating the fidelity of these various flux estimation approaches. Finally, a comparison against land surface model reproductions of spatial fields of the latent heat flux are undertaken, identifying the critical period of monsoonal transition in Northern Australia as an evaluation case.

2. DATA AND METHODS

2.1. CLM and NOAH land surface schemes

The Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004) produces time series of land surface state (e.g., soil moisture and surface temperature) and flux (e.g., latent and sensible heat flux) parameters through simulation of four distinct land surface models (LSM). The data employed here are 3 hourly, 0.25 degree data covering Australia for the period 2005-2006. Only two models provided data at this increased resolution: the Community Land Model (CLM) (Dai et al., 2003) and the NOAH model (Chen et al., 1996). For more information about GLDAS, see http://ldas.gsfc.nasa.gov/. For the analysis undertaken here, the model time-step between 1200-1500 local time is used. In compiling the model data from CLM and NOAA, weekly averages of the 1200-1500 model timestamp were used to simplify assessment and focus on broad scale patterns and changes in flux development.

2.2. SEBS based latent heat flux

A primarily remote sensing based retrieval scheme is employed to provide estimates of latent heat flux at the time of the satellite overpass. Using the Surface Energy Balance System (SEBS) model (Su, 2002), remote sensing data derived predominantly from NASA's Aqua satellite were compiled to produce instantaneous surface heat flux estimates across Australia for the period 2005-2006. The data represent 0.05 degree spatial resolution fields of instantaneous latent heat at approximately 1400 local time. Specific sensors that were employed to produce the satellite observations include: *Atmospheric Infrared Sounding Radiometer* (AIRS) for surface temperature, air temperature and pressure; *Cloud and Earth Radiant Energy System* (CERES) for incoming shortwave and longwave radiation, and emissivity; *Moderate Resolution Imaging*

Spectroradiometer (MODIS) for albedo and land-cover; and *Advanced Very High Resolution Radiometer* (AVHRR) for LAI, vegetation fraction and NDVI.

The only non-remote sensing based data that were used in the heat flux retrievals were wind-speed vectors obtained from the Global Modeling and Assimilation Office (GMAO). The resulting product represents a unique data set that is largely independent of the need for local scale forcing. A deliberate effort was made to only utilize data that is operationally available from either satellite sensors or as model forcing fields. However, this comes at a cost of spatially complete coverage, with issues of cloud and meteorological condition, satellite swath overlap, and data quality issues affecting the spatial extent available. To increase the spatial representation of the data, 7-day averages of the SEBS output were compiled. Pixel averages are calculated based upon the number of surface retrievals available at that pixel, with a minimum of 3 required to be included in the 7-day average. Where swaths overlap, a logical expression is developed to identify missing data, single value, or a pixel averaged value, depending on whether there are 0, 1 or 2 overlapping pixels. Even with these 7-day averages, there remain significant data gaps within the resulting fields.

While the Princeton ET product is in a preliminary stage of assessment, extensive applications of the SEBS modelling approach and evaluation of surface flux data can be found in Su et al. (2005), McCabe and Wood (2006) and Vinukollu et al. (2008).

2.3. Gridded precipitation data

Precipitation data from the Bureau of Meteorology (http://www.bom.gov.au/jsp/awap/rain/index.jsp) were used as a means of evaluating the fidelity of the land surface model and satellite based estimates of latent heat flux. These data, derived from in-situ gauge measurements, are interpolated to produce a 0.05 degree gridded field. Weekly precipitation totals are calculated, with the time stamp present in subsequent figures identifying the end of the 7-day cumulative period. Further information on the climatological data used here can be found in Jones et al. (2007).

3. RESULTS

3.1. Remote sensing and model based retrievals compared to flux tower data

One of the key difficulties in examining the accuracy of satellite based retrievals of evapotranspiration is the provision of high-quality in-situ measurements. While obtaining spatially and temporally consistent records of flux data is a challenge, surmounting the particular spatial and temporal scaling issues that are related to any intercomparison exercises are equally significant (McCabe and Wood, 2006). Regardless of these complications, tower based data remain a valuable source of information with which to assess both model and remote sensing based estimates of latent heat flux (Su et al., 2007). In this analysis, gap-filled hourly flux data from the Tumbarumba OZFlux site are averaged at the time of the satellite overpass (1300-1400) to produce equivalent 7-days averages throughout the year, in line with the production of similar periods for the GLDAS and SEBS output. Co-located SEBS and GLDAS data were extracted and compared with flux-tower estimates, as shown in Figure 1 below.

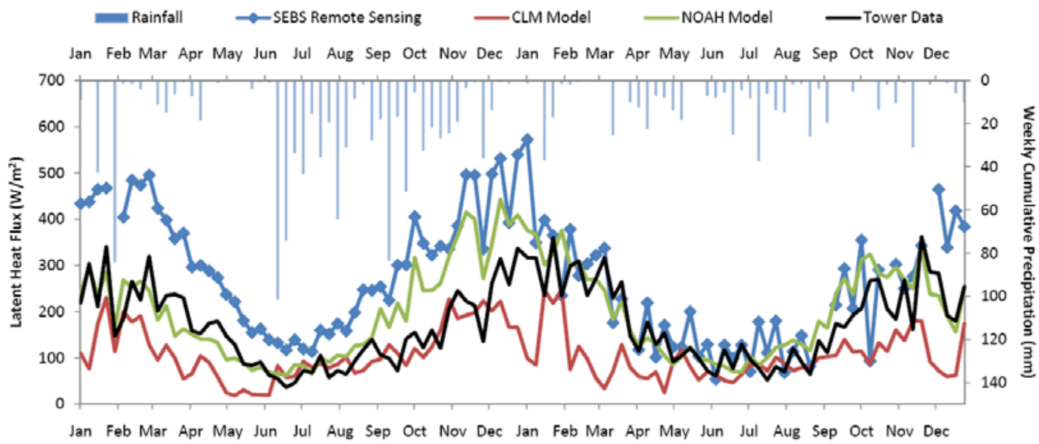

Figure 1. Comparison of 7-day averaged Tumbarumba tower data (1300-1400) for the years 2005 and 2006 (black line) with co-located 0.25 degree land surface model output from CLM (red) and NOAH (green), together with 0.05 degree SEBS remote sensing based estimates (blue). Rainfall data are derived from above canopy in-situ measurements at the Tumbarumba field site and are cumulative 7-day totals.

The Tumbarumba monitoring site is located in the Bago State forest in south-eastern NSW. It is classified as a wet sclerophyll forest, with an average tree height of 40 m. Elevation of the site is 1200 m and mean annual precipitation is 1000 mm (see http://www.cmar.csiro.au/ozflux/monitoringsites/tumbarumba/index.html). As can be seen, even with the significant scale mismatches inherent across the data streams, there is considerable agreement in the reproduction of the seasonal cycle. However, there is less agreement when examining the magnitude of flux variation at weekly scales, particularly between the two land surface models. The CLM output display a reduced amplitude across 2005-2006, while NOAH results reflect more accurately the development of the seasonal cycle throughout the years (in comparison to the SEBS and tower data). Of interest is the good agreement in 2006 (a seemingly dry year) between NOAH, SEBS and flux-tower data, in comparison to early 2005 – although the increasing trend during the period July-Dec 2005 is well represented. Pearson correlation co-efficient (r) between SEBS results and CLM, NOAH and tower data are 0.58, 0.77 and 0.75 respectively for the entire period (n = 98). Interestingly, correlation analysis on years 2005 (n=51) and 2006 (n=47) separately, reveal increased correlations for 2005 (0.72, 0.87, 0.90) compared to 2006 (0.37, 0.74, 0.77) for SEBS to CLM, NOAH, and tower data respectively. Preliminary investigation into the cause of the varying bias between SEBS data and tower observations reveal that there is an average weekly flux closure imbalance during 2005 of approximately 50 W/m^2, which is reduced to 20 W/m^2 in 2006. Further, the remotely sensed based radiation estimates, while representing well the average responses over the 2005-2006 period, display a bias of approximately 60-90 W/m^2 during this period.

3.2. Assessment of hydrological consistency in land surface model and remote sensing data

Evaluation of continental scale surface flux estimates is a considerable challenge, whether outputs derive from land surface modelling efforts or remote sensing retrievals. One approach proposed to address this is to examine the degree of hydrological consistency within retrieved fields (McCabe et al., 2008) as a means of determining the confidence of evaluated data. The approach is based on the expectation that a hydrological field should reflect a response to a forcing field i.e. that evaporation will increase in response to precipitation events, relative to areas that were not affected by the rainfall. Figure 2 illustrates a sample of this analysis, with weekly averages derived from the first 3 months of 2006 for CLM, NOAH and SEBS respectively.

The land surface model data display a marked boundary between areas of increased evaporation (> 300 W/m^2) in northern and eastern Australia, and decreased evaporative response (50-100 W/m^2) most elsewhere. Of particular interest across all three panels is the SEBS latent heat flux response stretching from north-west to south-west Western Australia. For each of the 7-day periods developed from the SEBS data (corresponding to weeks ending Feb 18, Mar 4 and April 15 respectively) a significant latent heat flux response is noticeable either as a distinct band stretching north-south across Western Australia (Week 9), or as more distributed patterns across north-western Australia and central Northern Territory to central Queensland (Week 7 and 15). The SEBS results from Week 9 (central column in Figure 2) display considerable agreement with 0.05 degree BoM rainfall maps for a significant rainfall accumulation across Western Australia – results that are completely missing in the CLM data, and suppressed (and geographically shifted) in the NOAH output. These results are curious, because the land surface models use the same forcing data, so disparity in model results is then a function of parameterisation and model physical process descriptions. Similar results in this region are also evident in Week 7 and Week 15, with strong evaporative response evident in the SEBS data as a result of precipitation events in the same week.

Results are also reflected on the other side of the continent, with SEBS flux response in central Queensland and north-eastern Northern Territory in good agreement with rainfall observations. Rainfall patterns are reasonably well represented in the NOAH flux data as well, although to a lesser degree and with considerably less spatial coherence than in the SEBS data. While there is some representation in the CLM data in this region, values seem to be amplified (northern Australia) or suppressed relative the other data-sets.

3.3. Identifying the transition of the monsoonal system in Northern Australia

While the land surface models employed here are not fully coupled schemes (in terms of land-atmosphere coupling), they do seek to represent the hydrological conditions of the terrestrial surfaces as a response to atmospheric forcing. The most significant hydrometeorological event in Australia’s northern regimes is the transition between wet to dry season (and vice-versa). This is a cycle that is repeated in many arid and semi-arid regions around the world (i.e. African Sahel, south-western United States) and plays a critical role in the biodiversity, ecology and hydrology of these regions. Modelling the onset and transition (retreat) between these regimes is an area of considerable interest (Drosdowsky, 1996; Barlow et al., 1998), particularly in identifying important land-atmosphere interactions such as possible soil moisture-precipitation feedbacks (Zhu et al., 2005).

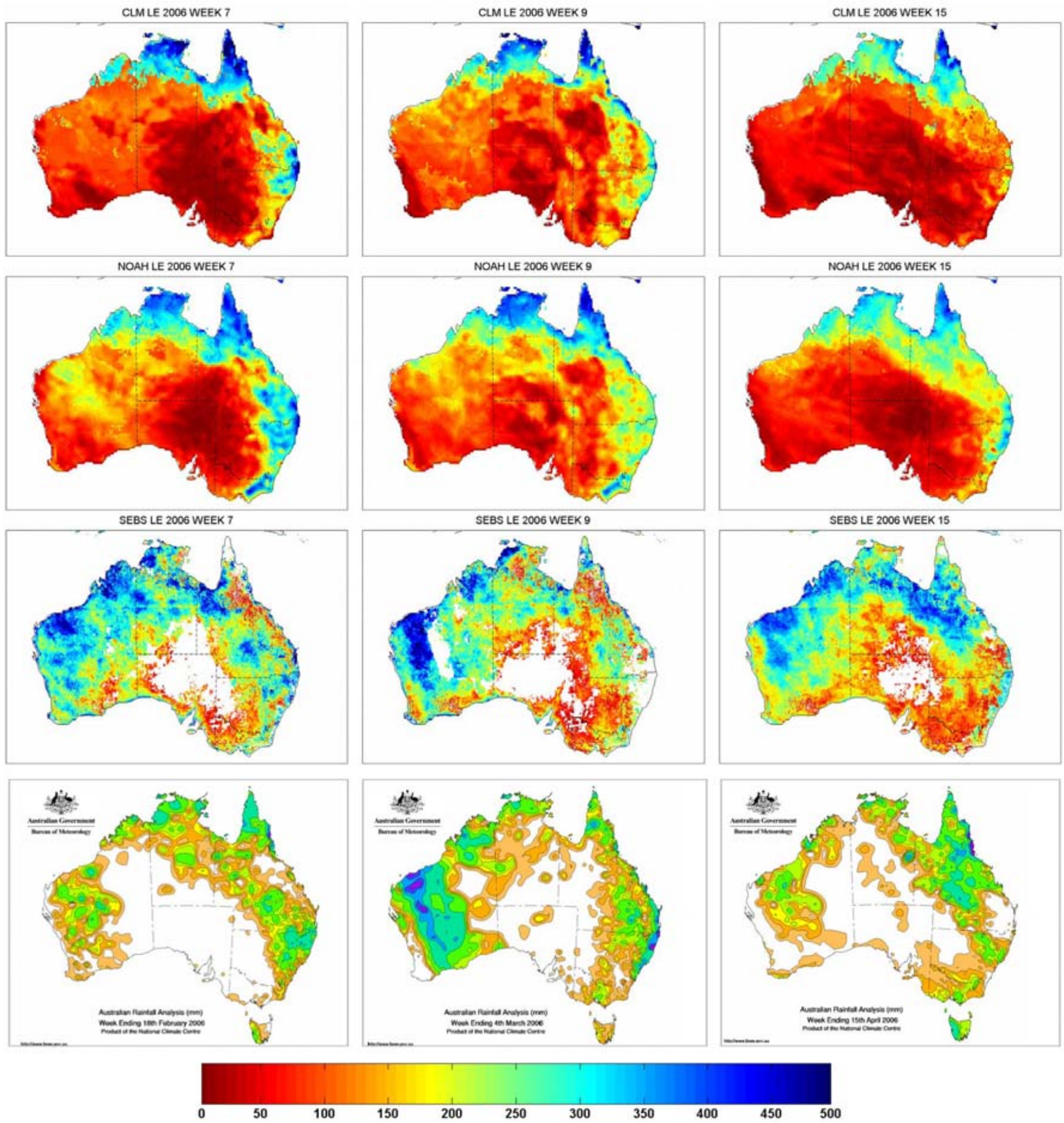

Figure 2. CLM, NOAH and SEBS output of latent heat flux for three unique 7-day events during 2006 compared with cumulative rainfall determined from gauge data (courtesy of Bureau of Meteorology) for the same period. Colour bar represents the latent heat flux.

Figure 3 presents eight consecutive weeks from March 25 – May 13, a period encompassing the expected retreat of northern Australia's wet season (generally March to early April). Panels are arranged horizontally, with 7-day average flux values from the CLM, NOAH and SEBS data, together with BoM rainfall observations. As can be observed, there is considerable variability between the model responses (CLM and NOAH) and the SEBS remote sensing retrievals of latent heat flux over the northern part of Australia. In particular, the duration of wet-season related latent heat flux in the NOAH response can be seen to extend well beyond available precipitation accumulations (see Week 16 onwards in BoM data). On the other hand, CLM 'dries-out' quite rapidly, although manages to maintain some response in the very northern regions of Australia. However, this is offset by an almost uniform spatial pattern of flux between 0 – 75 W/m^2 across the rest of the continent, even during periods of obvious rainfall forcing. The SEBS 7-day latent heat flux values on the other hand, represent a more reasonable response to precipitation forcing, with successive drying out through the northern regions, while maintaining an active and rapid response to incident rainfall events occurring in the north-west and south-west Western Australia (Weeks 17, 18 and 19) that are absent from the land surface models (also eastern Australia in Week 19). Whether the SEBS flux response in 'non-raining areas' of approximately 50–100 W/m^2 are representative, requires further investigation.

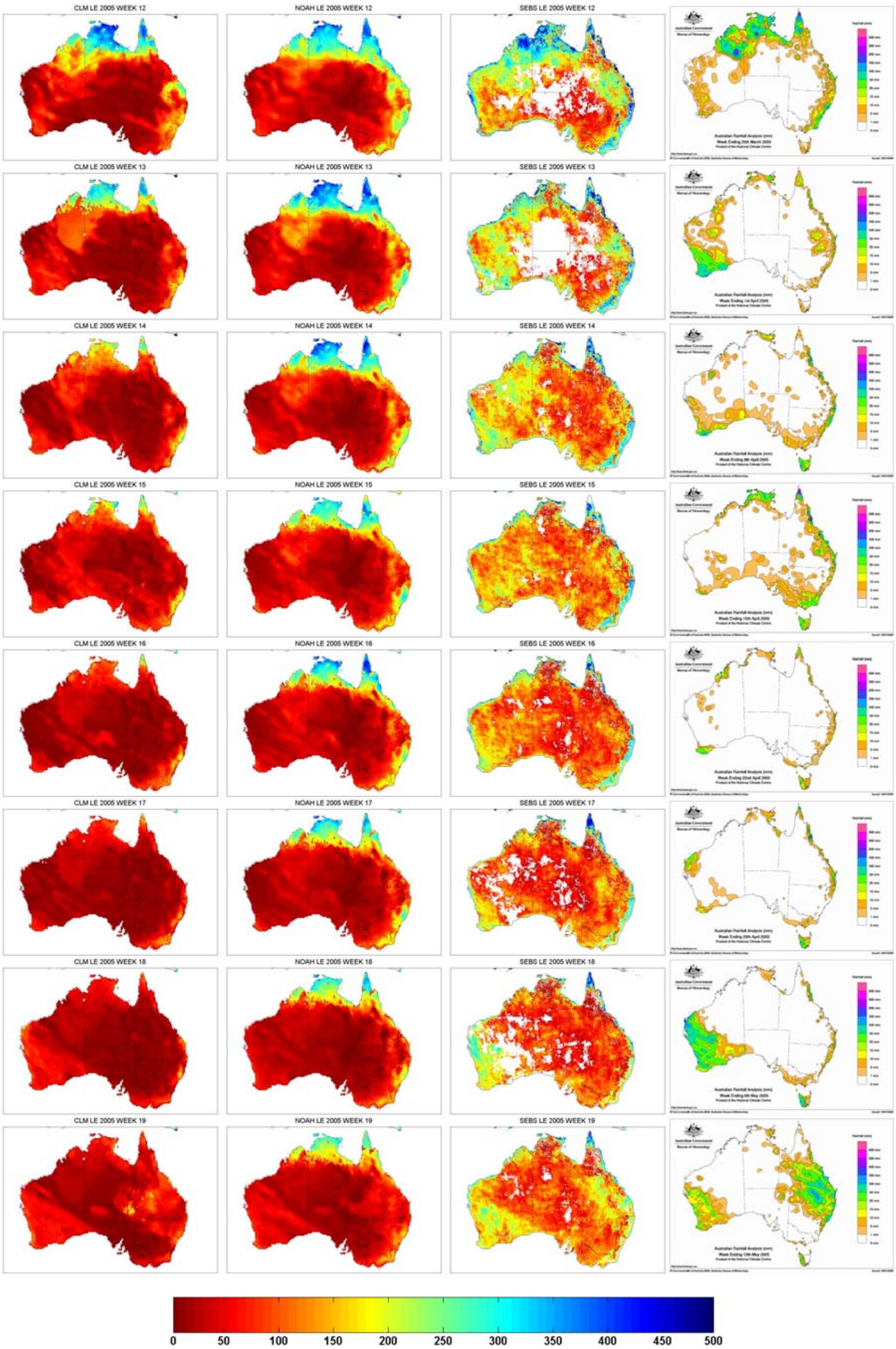

Figure 3. Model representation of the transition of the monsoon in Northern Australia during 2005, through analysis of land surface model output, remote sensing latent heat flux and BoM rainfall data.

4. DISCUSSION AND CONCLUSION

Evaluation of land surface models, whether at the local or global scale, remains a challenging task. Likewise, the validation of continental scale remote sensing presents its own unique challenges: tower data are generally too locally representative and land surface models are often plagued by parameterisation issues and inadequate (or poorly described) process representations. Common to both approaches is the need for independent sources of data to assess the accuracy of the modelled phenomena. For land surface modelling and remote sensing based approaches, these should naturally relate to their capacity to reproduce independently observed, but hydrological linked, processes. While land surface models seek water balance closure through construct, often resulting in misrepresentations of the hydrological response (as observed here) remote sensing based approaches provide an independent means to examine hydrological response without the constraint of water budget closure. The fidelity of the remote sensing retrieval should be clearly identified through linked remote sensing observations (i.e. precipitation > soil moisture > latent heat flux > water vapor), if confidence in the retrievals are to develop. However, resolving the qualitative (pattern matching) with quantitative (value matching) quandary requires ongoing work. While the hydrological consistency approach as presented here only provides a qualitative evaluation of estimated response, the next obvious step is to integrate these independent observations to improve process representation or model parameterisations. Whether this develops through a process such as data assimilation (which has its own limitations and complexities) or some other form of statistical merging is an area of needed investigation.

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